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तापीय न्यूट्रान रेडियोग्राफी — अनुशंसित रीतियाँ

Indian Standard

THERMAL NEUTRON RADIOGRAPHY — RECOMMENDED PRACTICES

ICS 77.040.20

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

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Price Group 4

Non-Destructive Testing Sectional Committee, MTD 21

FOREWORD

This Indian Standard was adopted by the Bureau of Indian Standards, after the draft finalized by the Non-Destructive Testing Sectional Committee had been approved by the Metallurgical Engineering Division Council.

Neutron Radiography (NR) uses neutron as the penetrating radiation for radiographing materials and components for evaluation of defects and characterization. Neutrons interact with nucleus of the atom of materials under test whereas X- and gamma-rays interact with the electron cloud of atom resulting in wide difference in absorption characteristics of objects for these two beams. This difference is used in neutron radiography to seek informations not available from X- or gamma-radiography. Thermal neutron radiography is used for different applications in various industries (nuclear, aerospace, defence, metallurgy). In nuclear industry, NR is most useful for radiography of irradiated nuclear fuel and other reactor components for defect evaluation and dimensional measurements. High attenuation of neutrons by hydrogenous materials provide powerful means to radiograph explosive charges, oils, seals, composites and gaskets in different metallic assemblies.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

THERMAL NEUTRON RADIOGRAPHY — RECOMMENDED PRACTICES

1 SCOPE

This standard covers the recommended practice for thermal neutron radiography of materials which provides the basis for good working practices for producing high quality radiographs. This standard deals with different types of neutron sources and the beam characteristics, moderation and collimation techniques, exposures technique, image recording methods and image quality.

2 NEUTRON RADIOGRAPHY

Neutron radiography is basically similar to X-radiography in which the penetrating beam of neutrons are allowed to interact with the object and the modulated beam is recorded in a suitable recording medium for macroscopic object details. The mode of attenuation of neutrons by materials is different from that of X-rays. X-ray interact with the orbital electrons, resulting in increase of attenuation coefficients with increasing atomic number. Whereas neutrons interact with the nucleus and the interaction is governed by the type of nuclei resulting random variation in attenuation. Fig. 1 shows the mass attenuation coefficients for X-rays and thermal neutrons. It may be noted that neutron attenuation is generally high for low *Z* material and generally low for high *Z* material.

The basic neutron radiographic set up consists of a fast neutron source, moderator, collimator, object and recording medium as shown in Fig. 2. All the available neutron sources produce neutrons in the high energy

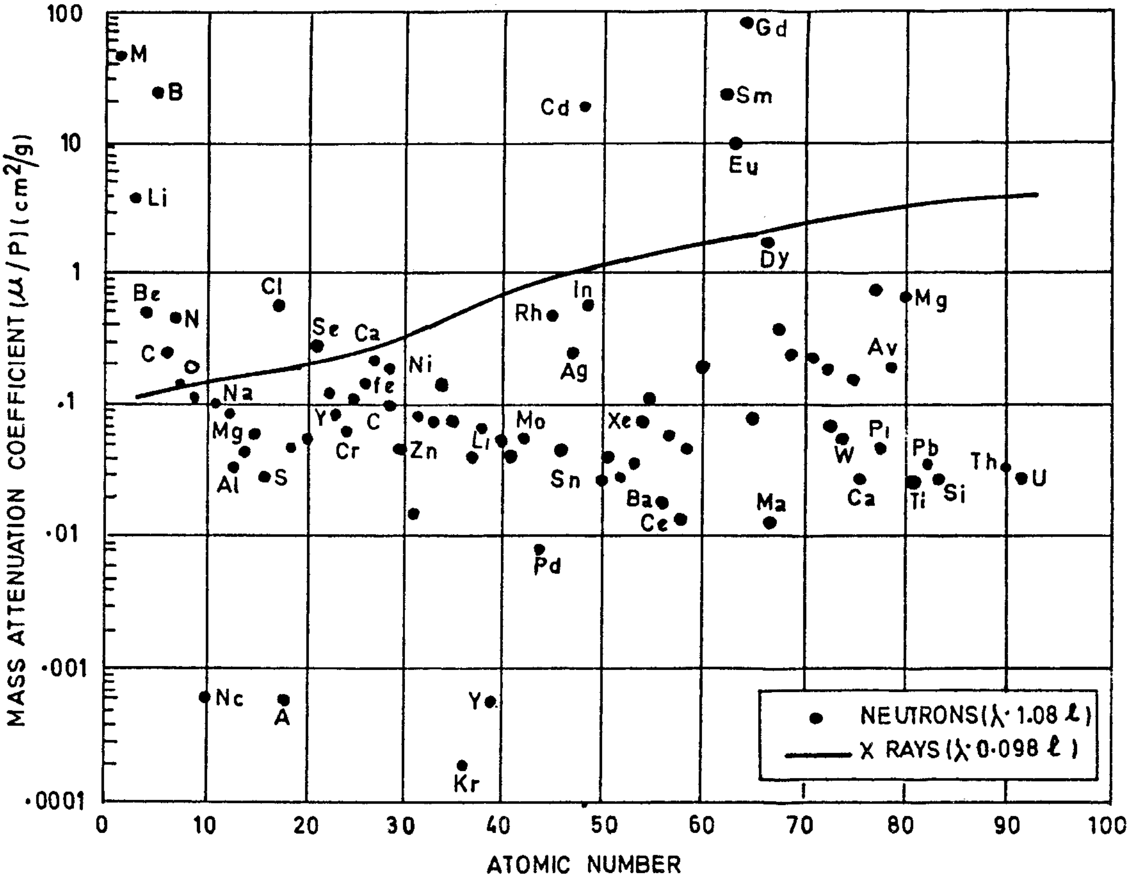


FIG. 1 APPROXIMATE MASS ATTENUATION COEFFICIENTS AS A FUNCTION OF ATOMIC NUMBER FOR X-RAYS AND THERMAL NEUTRONS

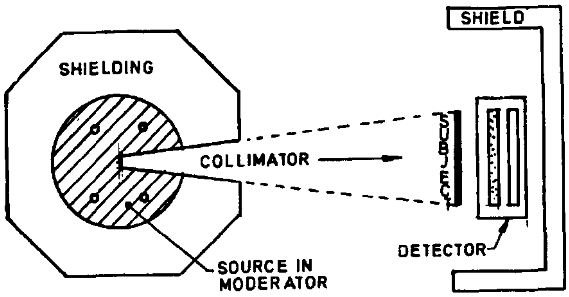


FIG. 2 TYPICAL ARRANGEMENT OF BASIC EQUIPMENT FOR THERMAL NEUTRON RADIOGRAPHY

range (a few electron volts) and they need to be slowed down to lower energy level (a few electron volts) to make them suitable for thermal neutron radiography. Neutrons are slowed down to low energy levels using moderating materials such as water, heavy water, graphite, beryllium and polyethylene placed around the fast neutron source. As neutrons move in a completely random manner in the moderator, collimators are used to extract directional neutron beam for imaging.

3 NEUTRON SOURCES

3.1 Any one of the following types of neutron sources can be used for carrying out NR:

a) Nuclear reactor,
b) Accelerators, and
c) Sub-critical assemblies.

3.1.1 *Nuclear Reactors*

In a Nuclear Reactor neutrons are produced by fission of fissile material like uranium. Reactor neutrons are slowed down to the thermal energy (0.03 eV) by suitable moderator like heavy water or graphite. Proper cooling and control system are provided for safe operation of reactor. Nuclear reactor can provide thermal neutron flux of 10^{11} to 10^{13} n cm^{-2} sec^{-1} at the core of the reactor before collimation. A typical radiography intensity available is around 10^5 to 10^8 n cm^{-2} sec^{-1} at the image plane for radiography. High collimation possible with nuclear reactors provide high resolution radiographs.

3.1.2 *Accelerators*

This is a general name given to machines that accelerate a beam of charged particles (protons, deutrons, alphas) and direct them to a target as shown in Fig. 3. An interaction takes place between the bombarding particles and the target atoms resulting in the expulsion of neutrons. Some of the typical reactions used in these accelerators are:

$$ {}_{1}^{3}\mathrm{T} + {}_{1}^{2}\mathrm{D} \;\text{———}\; {}_{2}^{4}\mathrm{He} + {}_{0}^{1}\mathrm{n} + 17.6\ \mathrm{MeV} $$

$$ {}_{4}^{9}\mathrm{Be} + {}_{1}^{2}\mathrm{D} \;\text{———}\; {}_{5}^{10}\mathrm{B} + {}_{0}^{1}\mathrm{n} + 4.3\ \mathrm{MeV} $$

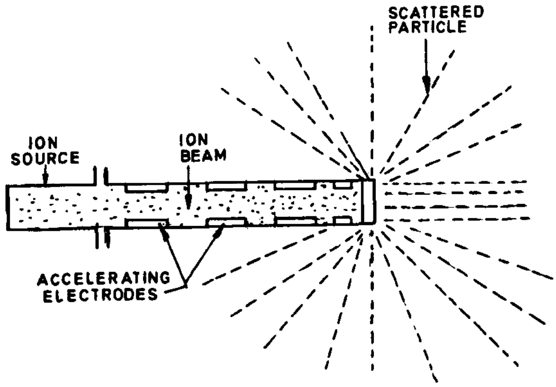


FIG. 3 SCHEMATIC DIAGRAM OF A PARTICLE ACCELERATOR

High energy X-ray machines can also be used to produce neutrons using beryllium or uranium target by (X, n) reaction. The radiographic intensity available is in the range of 10^3 to 10^6 n cm^{-2} sec^{-1} after collimation and moderation.

3.1.3 *Radioisotopes*

Radioactive nuclei called radioisotopes are in constant state of decay by emission of alpha, beta or gamma rays. Beryllium has the lowest neutron binding energy (1.6 MeV) and it is used as target with both alpha and gamma emitting isotopes to produce neutrons as shown in Fig. 4. Isotopes like californium 252 decay by spontaneous fission giving sufficient neutrons. Since it takes long time to produce this isotope in the reactor, it is quite expensive. However it is quite attractive from the point of its portability for site neutron radiography jobs. This isotope source gives a neutron intensity of order 10^2 to 10^5 n cm^{-2} sec^{-1}. Some of the useful radio isotopic neutron sources are given in Table 1.

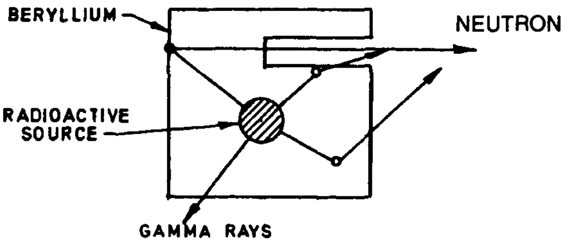


FIG. 4 ISOTOPIC NEUTRON SOURCE

3.1.4 *Sub-Critical Assemblies*

Sub-critical assemblies are used to increase the neutron flux of non-reactor based sources especially with radio isotopes. This is similar in construction to a small thermal nuclear reactor and it is not capable of sustaining chain reaction. Neutron source is placed at the core of the assembly and the fission process that

Table 1 Radioisotopic Neutron Sources

(*Clause* 3.1.3)

Sl No.	Source	Half-Life	Reaction	Neutrons per curie per sec	Average Neutron Energy (MeV)
(1)	(2)	(3)	(4)	(5)	(6)
i)	^{124}Sb-Be	60.3 d	(,n)	1.3×10^6	0.024
ii)	^{210}Po-Be	138 d	(,n)	2.5×10^6	4.2
iii)	^{241}Am-Be	458.1 y	(,n)	2.2×10^6	4.0
iv)	^{226}Ra-Be	1 620 y	(,n)	1.5×10^7	3.9
v)	^{228}Th-Be	1.9 y	(,n)	2.0×10^7	4.0
vi)	^{227}Ac-Be	21.8 y	(,n)	1.5×10^7	4.0
vii)	^{232}Cf	2.65 y	Spontaneous	4.3×10^9	2.3

takes place in the fuel of the assembly will lead to enhancement of neutron output of the source by many order of magnitude.

A typical sub-critical assembly with Cf 252 source can provide a multiplication factor of around 30. Licensing and safety precautions required to be followed are similar to that of required for a nuclear reactor. These assemblies provide better cost efficiency compared to a reactor and high neutron fluxes with low gamma contamination. The neutron flux available is however less than that of nuclear reactor.

3.2 Characteristics of Sources

3.2.1 The important characteristics of different neutron sources are given in Table 2.

Since high intensity is available in nuclear reactor, NR using nuclear reactor is preferred because of the short exposure time and better resolution.

3.2.2 In each of the above sources neutrons are removed from an atom by a nuclear transmutation process and emerge in enormous energy range from 10^{-4} eV to 10^7 eV. Energy of most interest for thermal neutron radiography is about 0.03eV, and it is the energy at which neutrons are in thermal equilibrium with its surroundings. It is important from the point of view of radiography as neutrons in this energy level exhibit better absorption characteristics for most of the materials as shown in Fig. 1. Further most of the detectors are very efficient in thermal energy level for image recording. Neutrons are classified as per their energy as given in Table 3.

Thermal neutrons are obtained by slowing down of fast neutrons by elastic collision with the atoms moderator until their average kinetic energy is equal to that of atoms of moderating medium. The neutrons distributed in a completely random manner in the moderator are extracted in a directional beam for imaging using collimator.

4 NEUTRON BEAM

4.1 Neutron beam parameters that affect image quality in radiography are energy, intensity, geometry (beam collimation), composition (background radiation).

4.1.1 *Neutron Energy*

Most NR is carried out in the thermal energy range. However different energy neutrons are used for specific applications and they are obtained using beam filters.

Cadmium filter with combination of Indium converter foil on some applications gives sharp pictures. Cadmium absorbs all neutrons below 0.04 eV and so leave the beam relatively rich in higher energies. One of these 1.4 eV is the energy of a resonance in Indium at which cross section increases from 2×10^2 barns to 3×10^4 barns. For radiography of radioactive nuclear fuel pin, this combination has been found useful. Some other filter materials are — Beryllium, Boron, Sodium, Rhodium, and Gadolinium.

4.1.2 *Beam Geometry*

Different types of collimators used for beam extraction are show in Fig. 5. Beam size and intensity available

Table 2 Characteristics of Sources

(*Clause* 3.2.1)

Sl No.	Type of Source	Typical Flux n/cm²/sec	Resolution	Exposure	Characteristic
i)	Radio isotope	10^1 - 10^4	Poor to medium	Long	Stable operation. Medium investment cost, portable
ii)	Accelerator	10^3 - 10^6	Medium	Average	On-off operation, medium cost, possibly mobile.
iii)	Nuclear reactor	10^4 - 10^8	Excellent	Short	Stable operation, high investment, not mobile.
iv)	Sub-critical assembly	10^4 - 10^6	Good	Average	Stable operation, medium cost, not portable.

for radiography at the image plane is affected by the type of collimator used. The important parameters that affect the sharpness of image is the ratio of distance from entrance aperture to the image plane (*L*) to the diameter of entrance aperture (*D*). Higher the *L/D* ratio better will be the image sharpness and *vice versa*. But higher *L/D* ratios reduces radiographic film intensity available and require longer exposure time. So higher *L/D* ratio is possible with nuclear reactors. *L/D* ratio of at least 10 is preferred for any meaningful practical *NR*. The most widely used collimator is the divergent type which provides large field size for examination.

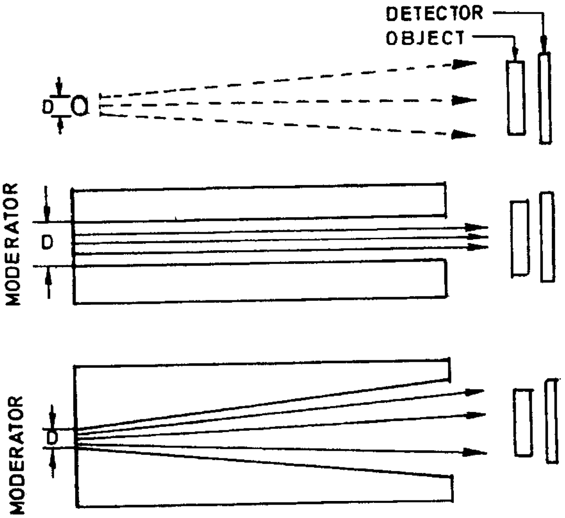


FIG. 5 NEUTRON COLLIMATORS (A) POINT SOURCE FOR EAST NEUTRON RADIOGRAPHY (B) PARALLEL-WELL COLLIMATOR (C) DIVERGENT COLLIMATOR

4.1.3 *Beam Quality*

Other thermal neutron parameters important to neutron radiography are:

a) degree of thermalisation of the neutron beam usually expressed as cadmium ratio;

b) intensity of gamma-ray associated with the neutron beam represented as ratio that is, *n/r* ratio; and

c) degree of scattered neutron present in the beam.

4.1.3.1 Measurement of above factors are required as they affect the image contrast and resolution in neutron radiography. Qualitative assessment and quantitative measurements can be done using image quality indicators.

4.1.3.2 *Image quality indicators*

Two types of image quality indicators are used in neutron radiography: (1) Beam purity indicator, (2) Sensitivity indicator. Beam purity indicator is a device used to measure beam characteristics such as thermal neutron content, gamma content, scatter neutron content and adequacy of L/D ratio. Sensitivity indicator is a device for measuring the combined effects of contrast and unsharpness on the sensitivity of detail visible in the radiography (Details regarding construction of beam purity indicator and sensitivity indicator and the procedures for measurements are described in a separate standard to be issued under the 'Method for Determining Image Quality in Thermal Neutron Radiography').

Table 3 Neutrons Classified According to Energy

(*Clause* 3.2.2)

Sl No.	Term	Energy Range
i)	Slow	0.001 e V to 10^3 e V
ii)	Cold	Less than 0.01 e V
iii)	Thermal	0.01 e V to 0.5 e V
iv)	Epi-thermal	0.05 e V to 10^4 e V
v)	Resonance	1.0 e V to 10^2 e V
vi)	Fast	10^3 e V to 20 MeV

5 RADIOGRAPHY TECHNIQUES

5.1 Set up Marking and Identification

Neutron beam should be aligned to the middle of the job and normal to the surface. Marking for proper identification of radiographs should be done with cadmium or plastic numerals. Some times the edge of the object should be pasted with cadmium or plastic foils to delineate the boundary.

5.2 Image Recording

Neutrons do not have direct action on films. In order to record the image carried by the transmitted neutron beam from the object, it is essential to use suitable material that absorb neutrons and produce secondary radiations such as electrons, photons, alpha particles that have photographic action. This material is typically in the form of foil of thickness 25 to 250 microns. These foils are called converter screens. The following two types of imaging methods are used for image recording in NR as shown in Fig. 6.

a) Direct image method, and

b) Indirect or transfer image method.

5.2.1 *Direct Image Method*

In direct image method a film is exposed along with converter screen. Prompt secondary radiation emitted by the converter foil causes the photographic effect on the film. This is similar to X-ray film exposure.

Most extensively used screen in direct imaging is 25 micron thickness Gadolinium foil. This technique produces very sharp image but disadvantage is its sensitivity to gamma radiation present in the beam which lowers contrast.

5.2.2 *Transfer Image Method*

In the transfer or indirect image method the converter screen is alone exposed along with the specimen in the neutron beam. The activated converter screen is transferred to dark room and kept with the film for image transfer. The activity build up on the screen and the activity transferred to the film during film transfer depend on the half life of isotope formed. This method is insensitive to gamma and hence most suitable for inspection of radioactive components. Most widely used converter screen are Indium (54 min half life) and Dysprosium (140 min half life) in thickness range of 100 to 250 microns. Properties of some other useful thermal neutron converters are given in Table 4.

5.2.3 *Exposure Technique*

In both direct and transfer image methods single converter screen is to be used as back screen only. Single coated films are preferred for direct exposure to get sharp images. Vacuum cassettes offer good film screen contact. However good quality spring loaded cassettes give reasonably acceptable results. A back cadmium screen of 0.5 mm thick is used during exposure to absorb back scattered neutron's reaching the image plane.

Table 4 Converter Screen in NR

(*Clause* 5.2.2)

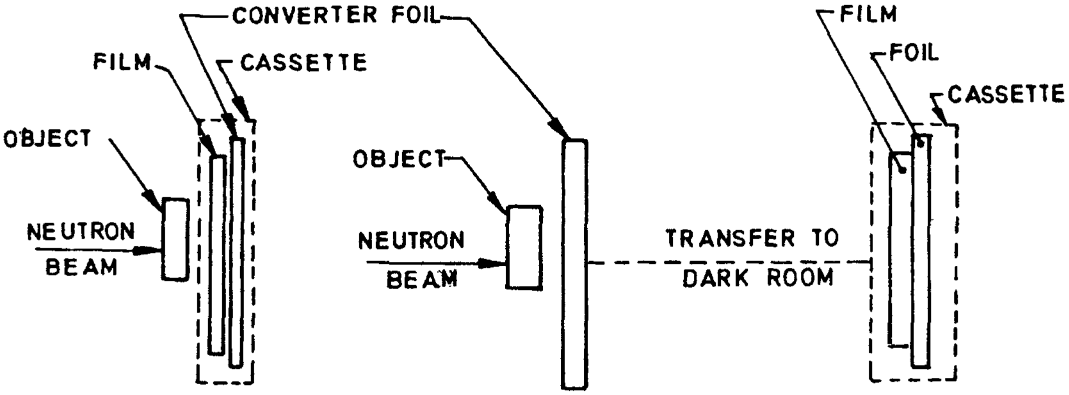
Sl No.	Material	Useful Reaction	Half-Life	Cross Section for Neutrons (barns)
(1)	(2)	(3)	(4)	(5)
i)	Lithium	$^{6}Li(n,\propto)\,^{3}H$	Prompt	910
ii)	Boron	$^{10}B(n,\propto)^{7}Li$	Prompt	3 830
iii)	Cadmium	$^{113}Cd(n,\gamma)\,^{114}Cd$	Prompt	20 000
iv)	Gadolinium	$^{155}Gd(n,\gamma)^{156}Gd$	Prompt	60 900
		$^{157}Gd(n,\gamma)^{158}Gd$	Prompt	254 000
v)	Indium	$^{115}In(n)^{116}In$	54 min	157
		$^{115}In(n)^{165m}In$	14 sec	42
vi)	Dysprosium	$^{164}Dy(n)^{165m}Dy$	1.25 min	2 200
		$^{164}Dy(n,\gamma)^{165}Dy$	140 min	800
vii)	Gold	$^{197}Au(n)^{198}Au$	2.7 days	98.8

5.3 Track Etch Detectors

Certain dielectric materials like plastic, polymers and mica when exposed to heavy particle radiation will record damage tracks. These tracks can be made visible by etching with an alkaline solution. Boron-10 based converter screens are used with polycarbonate or cellulose nitrate sheets and exposed in the neutron beam. After exposure the cellulose nitrate sheets are etched in 25 percent KOH solution at 70 degree for 30 min. Track-etch method produces very sharp image and it is also insensitive to gamma rays. The only disadvantage of this method is its translucent nature of the image and poor contrast.

6 EXPOSURE CHARTS

Exposure charts for combination of source beam



A DIRECT METHOD B TRANSFER METHOD

FIG. 6 DIRECT AND TRANSFER METHOD FOR PRODUCING A NEUTRON-IMAGE

intensity, converter screen thickness, material of job and film type should be prepared to obtain consistent high quality radiographs. One typical exposure chart is given in Fig. 7.

7 FILM PROCESSING

Film processing steps are similar to those used for development X- or Gamma-rays radiographs. For track etch method the recommended etching conditions by the supplier of track detectors are to be followed.

8 RECORDS

8.1 Proper records for neutron radiography should typically consist of following details:

i) Diameter of beam inlet aperture,
ii) Inlet aperture to object distance (L/D ratio),
iii) Characteristic neutron energy (Cd-ratio),
iv) Beam quality data as measured by beam quality indicator,
v) Type of film used,
vi) Material of converter foil and its thickness,
vii) Material of object radiographed and its thickness,
viii) Results of interpretation of radiography, and
ix) Radiographic sensitivity achieved as indicated by sensitivity indicator.

9 SAFETY PRACTICE

Safety precautions and practices to be followed in dealing with neutrons are given as under.

9.1 Personnel employed in NR should follow the safety precautions and procedures recommended by AERB (Atomic Energy Regulatory Board) and ICRP (International Committee for Radiation Protection). For further details regarding safety and use of neutron radiography the applicable regulatory agency (Atomic Energy Regulatory Board, Industrial and Radiation Safety Division, Niyamuk Bhavan, Anushakthi Nagar, Mumbai 400 094) is to be contacted.

9.2 Object placed in neutron beam gets activated depending on its activation cross section, neutron beam energy, intensity and half life of its decay. Object will retain the residual activity after the exposure. So it is strongly recommended to monitor the object surface activity with a suitable radiation monitoring device before handling the object. Objects showing high levels of activity should be kept aside so that its activity reduces to safe level for handling.

9.3 Training of Personnel

Training and certification of personnel is important in NR like other NDT methods to produce acceptable neutron radiographs. The personnel should be certified to the required level by the established National Agency.

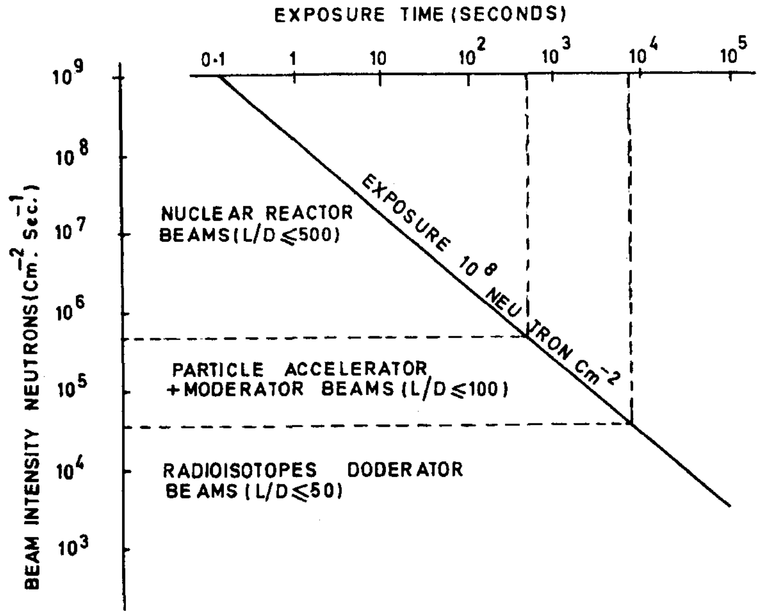


FIG. 7 EXPOSURE TIME CURVE AS A FUNCTION OF BEAM INTENSITY FLUX FOR HIGH RESOLUTION NEUTRON IMAGES (EXPOSURE 10^8 NEUTRONS cm^{-2} FOR DIFFERENT TYPICALLY AVAILABLE NEUTRON SOURCES

All the objects, cassettes, fixtures in around the target gets activated and their levels should be monitored before handling. Converter screens used for indirect exposure method such as indium, dysprosium, gold gets activated to high levels of radiation. These screens should be handled with gloves or tongs and should be moved in a shielded box. During transfer of screen to the film extreme care should be taken in handling the activated screen.

10 GLOSSARY OF TERMS USED IN NEUTRON RADIOGRAPHY

10.1 Attenuation Coefficient

Related to decrease in radiation beam intensity as it passes through matter.

Related Terms: Linear and mass attenuation coefficients.

10.2 Attenuation Cross Section

The probability of interaction with the target nucleus that results in the total absorption, usually expressed in barns.

10.3 Activation

The process of inducing artificial radio activity in a substance by subjecting it to bombardment by neutrons or other particles.

10.4 Barn

A unit of area used to express the area of nuclear cross section. 1 barn = $10^{-24} cm^2$.

10.5 Cassette

A light tight device used for holding film or converter screen and film in close contact during exposure.

10.6 Cross Section

The apparent cross-sectional area of the nucleus that is related to the probability of occurrence of a nuclear reaction by collision with a particle. It is not related to the geometrical cross-sectional area of the nucleus. It is given in units of area, that is, barn.

10.7 Direct Exposure Imaging

In this method both the converter screen and the film are exposed together.

10.8 Gamma Ray

Electromagnetic radiation having its origin in atomic nucleus.

10.9 Half Value Layer

It is thickness of an absorbing material required to reduce the intensity of a beam of radiation to one half its original intensity.

10.10 Indirect Exposure

An imaging method in which the converter screen capable of getting activated in a neutron beam alone is exposed. After exposure the activated screen is kept in contact with a film.

10.11 L/D Ratio

The ratio of the distance from the entrance aperture to the image plane (L) to the diameter of the entrance aperture (D). It is important parameter that affects resolution in neutron radiography.

10.12 Converter Screen

A screen or foil that converts the neutron beam into other radiation or light that exposes the radiographic film.

10.13 Linear Attenuation Coefficient

A measure of fractional decrease in radiation beam intensity per unit distance in material.

10.14 Mass Attenuation Coefficient

A measure of fractional decrease in radiation beam intensity per unit of surface density.

10.15 Moderator

A material used to slow down fast neutrons by elastic collisions with the atoms of moderating materials of light elements without much absorption, such as, hydrogen, deuterium, beryllium and carbon.

10.16 Neutron

A neutral elementary particle having a mass close to 1 a.m.u.

10.17 Neutron Radiography

A process of recording the transmitted (modulated) neutron beam intensity by an object in a recording medium.

10.18 Thermal Neutron

Neutrons having energies ranging between 0.005 eV and 0.5 eV. Neutrons in these energy range are in thermal equilibrium with its surrounding at temperature around 20°C.

10.19 Total Cross Section

The sum of the absorption and scattering cross sections.

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